

**Award #: NASA-AMES Research Grant Number NAG 2-1323**  
**Title: Advanced Opto-Electronics (LIDAR and Microsensor Development)**  
**Principal Investigator: Lee H. Spangler –Montana State University**  
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**Report Type: Summary of Research**  
**Technical Officer: Vern C. Vanderbilt**

**Lidar and Microsensor Development Final Report**  
**NASA-AMES Research Grant Number NAG 2-1323**  
**Joseph A. Shaw, Kevin S. Repasky, John L. Carlsten, David Dickensheets, Lee H. Spangler**

I. Objectives:

Our overall intent in this aspect of the project were to establish a collaborative effort between several departments at Montana State University for developing advanced opto-electronic technology for advancing the state-of-the-art in optical remote sensing of the environment. Our particular focus was on development of small systems that can eventually be used in a wide variety of applications that might include ground-, air-, and space deployments, possibly in sensor networks. Specific objectives were to:

- 1) Build a field-deployable direct-detection lidar system for use in measurements of clouds, aerosols, fish, and vegetation;
- 2) Develop a breadboard prototype water vapor differential absorption lidar (DIAL) system based on highly stable, tunable diode laser technology developed previously at MSU;

II. Accomplishments:

We accomplished both primary objectives of this project, in developing a field-deployable direct-detection lidar and a breadboard prototype of a water vapor DIAL system. The following summarizes each of these accomplishments.

**A. Develop a direct-detection lidar system**

As proposed, we built the “Multiple-Application Montana Lidar” (MAML), which is a direct-detection lidar designed to be flexible enough for use in a variety of applications with competing instrument needs by changing modules in the system as necessary. The objective was to build this instrument into a field-deployable form, which has been achieved. The modular design of this system allows it to be reconfigured, with modest modular changes, for applications ranging from measuring atmospheric aerosols and clouds (narrow field-of-view and optical filter) to profiling fish schools and measuring vegetation (wide field of view and optical filter).

Table 1 lists the specifications of the MAML system, Figure 1 shows a schematic diagram of the major electronic and optical components, and Figure 2 shows photographs of the system and its receiver optics. The system employs a robust commercial Nd:Yag laser operating at the frequency-doubled wavelength of 532 nm with 30 pulses per second (~130 mJ/per 10-ns pulse), a commercial Schmidt-Cassegrain telescope for the receiver collection optics, and a photomultiplier tube detector whose signal is digitized with a high-

speed analog-to-digital-converter card (ADC) at a rate of 100 Msamples/s with 14 bits dynamic range.

The primary unique feature of this lidar system is its dual-polarization receiver, which allows determination of the lidar depolarization ratio for every pair of shots (i.e., 15 times per second). The receiver polarization is rotated between orthogonal linear states for every laser shot by varying the voltage supplied to a liquid crystal variable retarder that is followed by a fixed linear polarizer. This avoids the trouble that arises when calibration is performed on separate detectors for orthogonal polarization channels, but does so with a loss of absolute simultaneity. This tradeoff results in a compact system that is less sensitive to misalignment, but quite easily transported and deployed on ground-, air-, or ship-based platforms.

A related accomplishment is the development of a breadboard lidar system that provides the capability of two-wavelength (1064 and 532 nm) aerosol measurements. While this system has not been packaged for field deployment, it operates through a roof port that we had installed as part of this effort. Currently we are using the two-wavelength lidar data to invert aerosol backscatter coefficients.

Table 1. Specifications for the Multiple-Application Montana Lidar system.

<b>Transmitter: Big Sky Laser CFR200, Flashlamp-Pumped Frequency-Doubled Nd:YAG</b>		
Wavelength	532 nm	
Pulse Repetition Rate	30 Hz	
Pulse Energy	118 mJ	
Beam Divergence	2.16 mrad	
Pulse Width	10 ns	
<b>Receiver: Celestron 8" Schmidt-Cassegrain Telescope</b>		
Focal Length	2265 mm	
Field of View	Variable up to 8.8 mrad	
Spectral filter	1 nm FWHM	
Detector	Hamamatsu Gated PMT	
<b>Signal Processing: Gage 14100, PCI-Based Digitizer</b>		
Sample Rate	100 MS/s (1.5 m	
	sampling period)	
Nominal Bit Depth	14 bits	
Data Rate	2.16 GB/hour (with 15 km maximum range	
	and with full resolution)	
<b>Polarization Discrimination: Meadowlark Optics Nematic Liquid Crystal Variable Retarder</b>		
System Depolarization Ratio Additive Error	< 0.4%	
<b>Instrument Size (W × L × H)</b>		
Optics Package	31 cm × 46 cm × 97 cm	
Electronics Rack	59 cm × 89 cm × 87 cm	

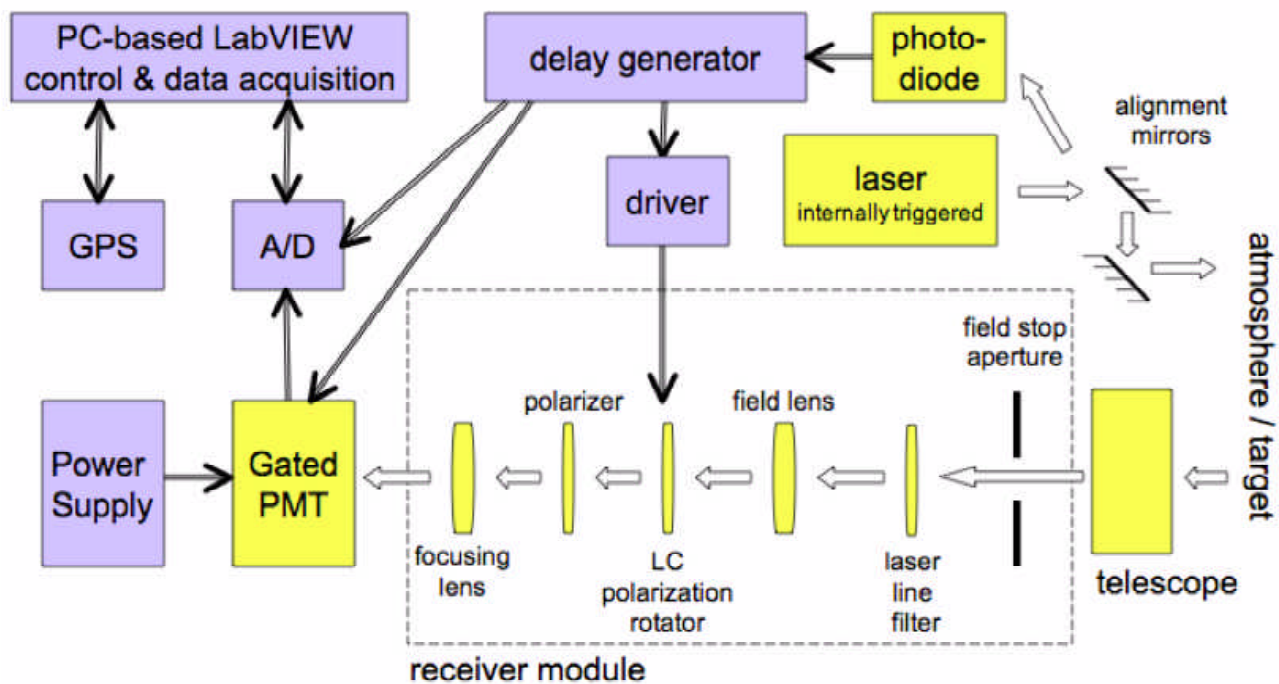
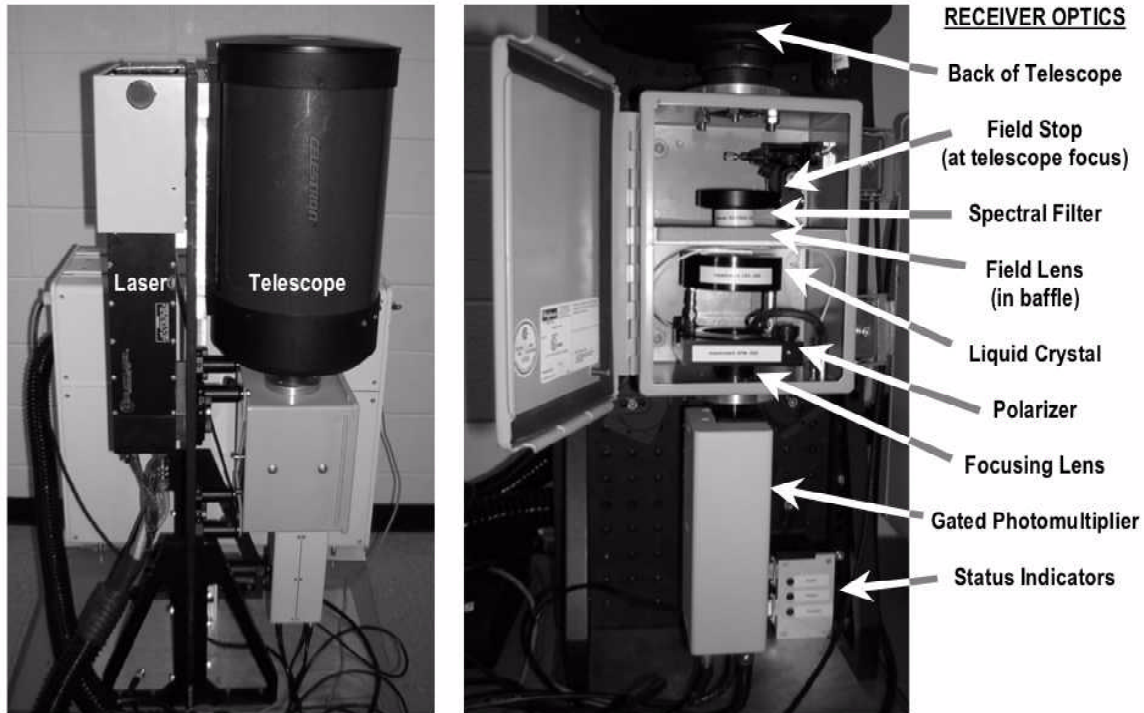


Figure 1. Schematic diagram showing electronic and optical components of the MAML system. A rack-mount computer controls the instrument with user-selected parameters and stores the raw data.



**Figure 2. Photographs of (left) the MAML dual-polarized lidar system and (right) the receiver optics module. The receiver field of view is varied with a user-selectable field stop.**

We have subjected the MAML system to a thorough sequence of calibration and characterization measurements to establish with a high degree of precision that the total polarization error is less than 0.4% (a factor of 2-4 less when viewing a target that is 20-50% polarized). A master's thesis was generated that describes the complete system engineering and characterization, along with its use in measuring clouds.

Figures 3, 4, and 5 show sample cloud data obtained with the MAML system operated from the roof-port laboratory at Montana State University during early 2005. The dual-polarization capability allows the lidar to discriminate between liquid water and ice crystals, providing an enormously useful dimension to cloud studies.

Figure 3 shows sixty-second range-time plots of the (top) co-polarized backscatter signal and (bottom) depolarization ratio, equal to the ratio of the cross-polarized and co-polarized signals. The co-polarized signal is measured with the receiver polarization aligned parallel to that of the transmitted beam, while the cross-polarized signal is measured with the receiver polarization aligned orthogonal to the transmitted beam polarization state. When looking at clouds, a nearly zero depolarization ratio indicates the presence of liquid water, which is comprised of essentially spherical drops that have no depolarizing capability by virtue of their symmetry. Conversely, a high depolarization ratio (typically up to 30 or 40%) indicates the presence of ice crystals, whose corners, edges, and generally asymmetric shape provides significant depolarization of the incident laser beam. In Figure 3, there are two primary cloud layers visible in the co-polarized backscatter signal (top), but only the higher layer, near 8 km, shows up in the

depolarization ratio plot (bottom). In this case, these are thin cirrus clouds that produce a fairly typical cirrus signature of approximately 30% depolarization.

Figure 4 shows an optically dense layer located just above 6 km altitude, which has low depolarization at the bottom, which decays into a high depolarization at the top of the layer. This is a reasonably typical signature of supercooled liquid clouds, but also could indicate the presence of multiple scattering (which can generate depolarization that increases with depth in the cloud). This problem of multiple scattering causing depolarization that increases with depth in the cloud arises if the lidar receiver field of view is not sufficiently narrow. We have the capability of reducing the field of view to minimize this problem.

Figure 5 shows lidar evidence of multiple scattering layers located between 7 and 9 km altitude, all of which are quite depolarizing. This is a particularly interesting example because it occurred during a period when the sky was extremely clear to the eye. Investigation of the meteorological conditions led to our identification of these scattering layers as dust transported to Montana from China. Previous studies have shown that desert dust can be picked up in wind storms from the Tibetan plateau and transported to the United States. No previous investigator has measured this sort of Asian dust in Montana, however. The closest measurements were in British Columbia and Utah.

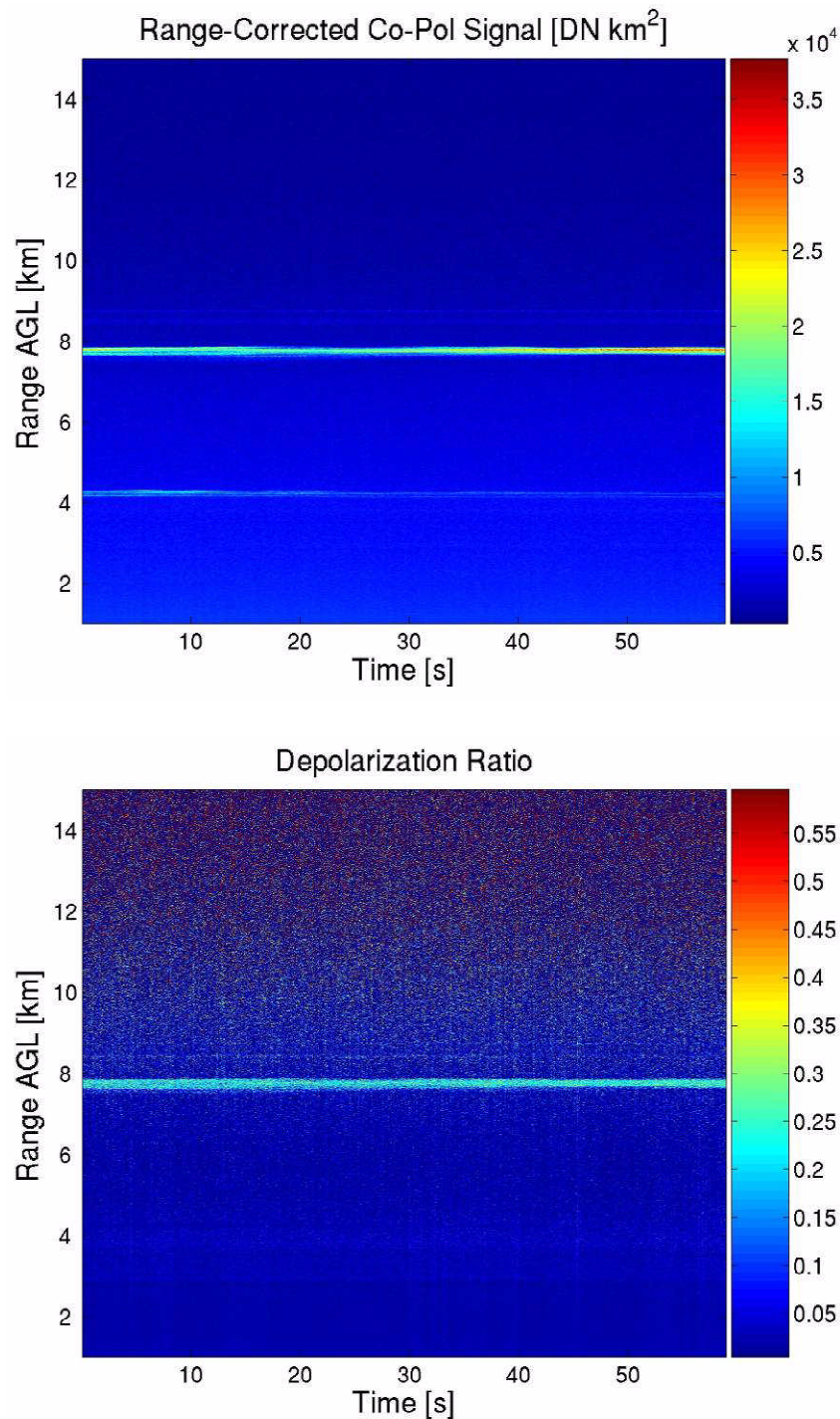


Figure 3: Lidar data for March 3, 2005, 04:19 UTC, showing multiple cloud layers with different depolarizations. (top) co-polarized backscatter signal showing a thin cloud layer near 4 km and a thicker layer near 8 km; (bottom) depolarization ratio, showing that the higher cloud is comprised of ice crystals ( $\sim 30\%$  depolarization) and that the lower cloud is liquid water (essentially zero depolarization).



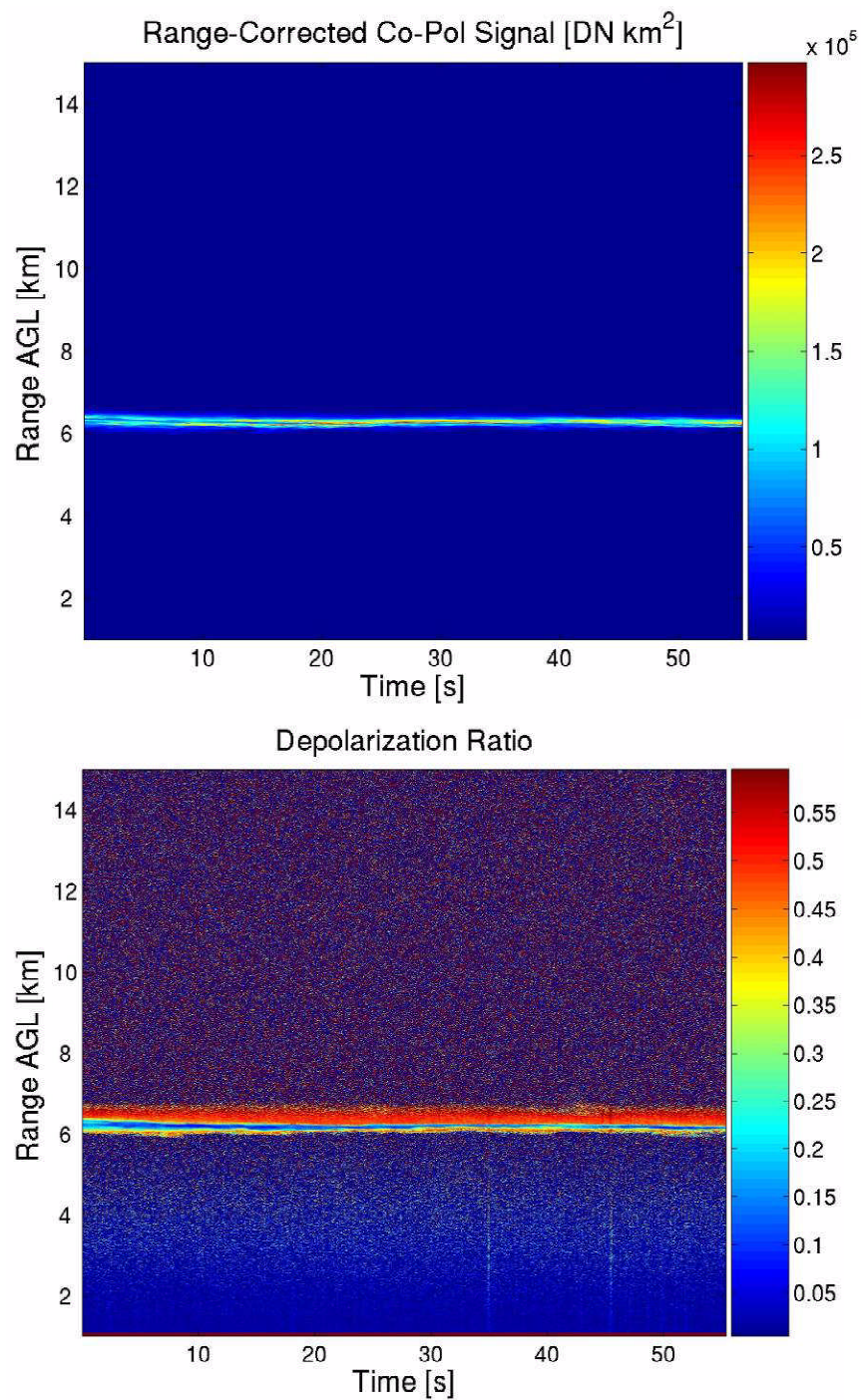
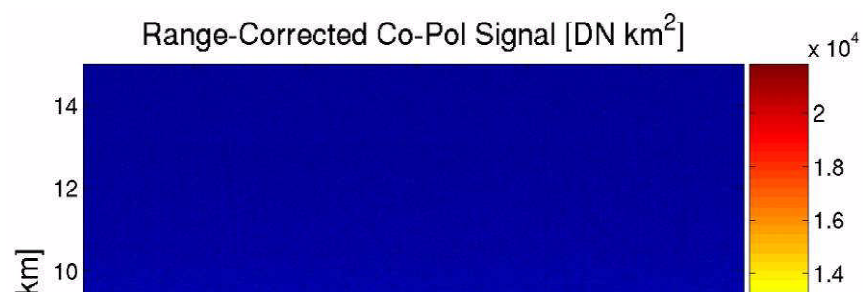


Figure 4: Lidar data for March 7, 2005, 23:04 UTC, showing a dense, low-depolarization cloud layer (at -37.8 °C).





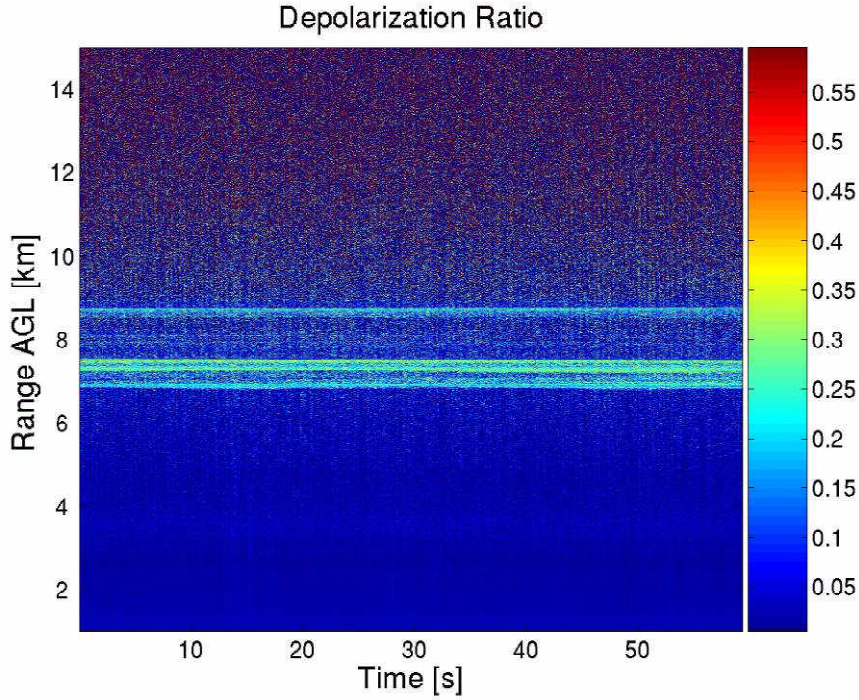
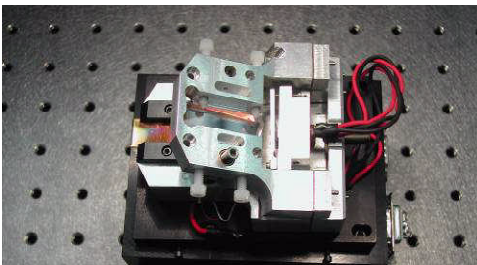


Figure 5: Lidar data for March 1, 2005, 03:32 UTC, showing multiple subvisual layers of depolarizing material. These layers were identified, through meteorological analysis, to be desert dust transported to Montana from western China.

## B. Develop a prototype water vapor differential absorption lidar using a diode laser

Our second objective was to develop a breadboard prototype of a differential absorption lidar system for measuring atmospheric water vapor with a tunable diode laser source. We have accomplished this task and are presently in the midst of refining the system to improve the signal-to-noise ratio.

The first major accomplishment toward meeting this objective was to build a tunable External Cavity Diode Laser (ECDL) at the appropriate wavelength near 830 nm and demonstrate that it could reliably tune to and across known water vapor absorption lines. Figure 6 shows a photograph and schematic layout of the ECDL system we built for this lidar system. This is an ECDL built in a Littman-Metcalf configuration, using an easily available commercial diode laser with a center wavelength of 830 nm. The external cavity arrangement allows us to tune the laser's output to a specific wavelength across a 17-nm coarse-tuning range. Fine tuning is achieved by varying the angle of the prism with a piezo-electric element.



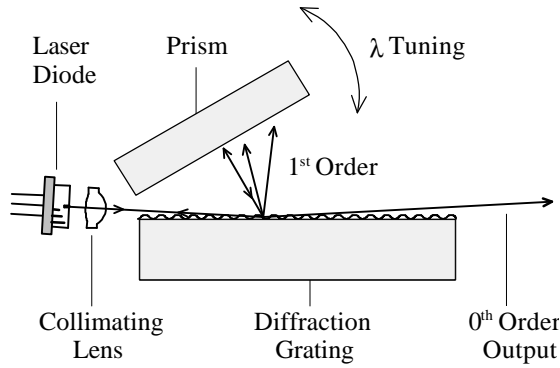


Figure 6. Littman-Metcalf External Cavity Diode Laser (ECDL) built at Montana State University for use in a differential absorption lidar transmitter.

Figure 7 shows the laser output spectrum, measured at three different tuning settings, indicating the wide range of tunability and the extremely narrow lineshape achieved at each setting. The output laser linewidth is less than 200 kHz, with a tuning range of greater than 20 GHz.

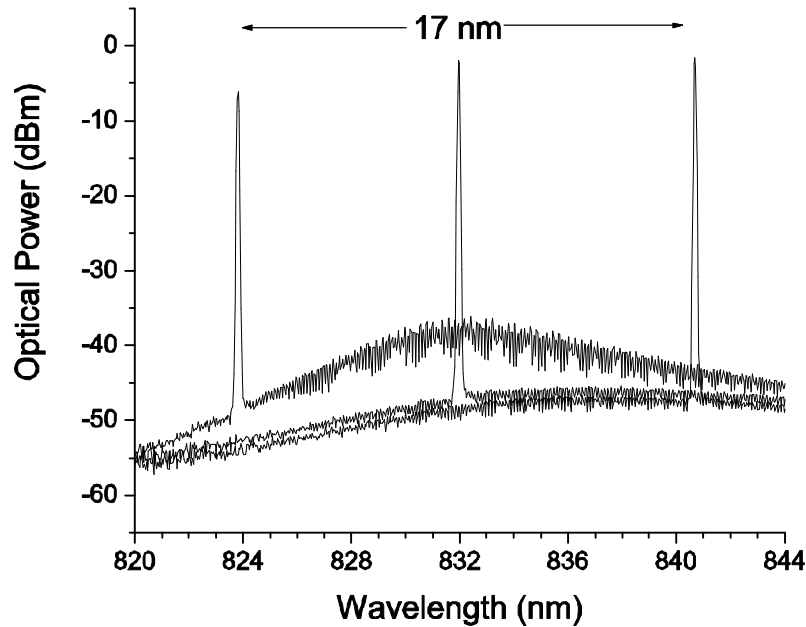


Figure 7. ECDL putput spectra measured at three different wavelengths, showing tunability and narrow linewidth.

A schematic diagram of the prototype system layout is shown in Figure 8. In this system, light from the transmitter ECDL is passed through two isolators, polarization optics (and a pickoff to provide sample measurements of the transmitted beam), and through an iris pair

to a tapered amplifier. This amplifier boosts the approximately 20 mW of continuous-wave optical power to a level more suitable to atmospheric lidar measurements. We continue to experiment with optical power levels. After another optical isolator and more polarization optics, the beam is passed through another iris pair into the atmosphere. Backscattered light is collected by a 28-cm-diameter Schmidt-Cassegrain telescope and focused through a narrowband optical filter to a fiber-coupled avalanche photodiode (APD) for photon-counting detection. The use of photon-counting detectors and moderate aperture size allows collection of the weak diode laser light at a level that is practical with minutes of temporal averaging.

Experiments conducted so far have used hard scattering targets located at approximately 0.86 km range. This has allowed us to test the laser tuning with sufficient return light, without requiring long time averages. We are experimenting with a variety of pulsing techniques, but are focusing on the approach of directly pulsing the tapered amplifier driver to generate 1 microsecond optical pulses. Figure 9 shows a measurement of relative transmission through the atmosphere as the system was tuned automatically across a water vapor absorption line at 829.022 nm. The excellent agreement between measurement and theory confirms the stability and accuracy of the tunable lidar system. Figure 10 shows initial pulsed results made with a hard target, which show that the same level of performance is maintained with a pulsed laser source. Work is in progress now to obtain similar measurements in the open atmosphere.

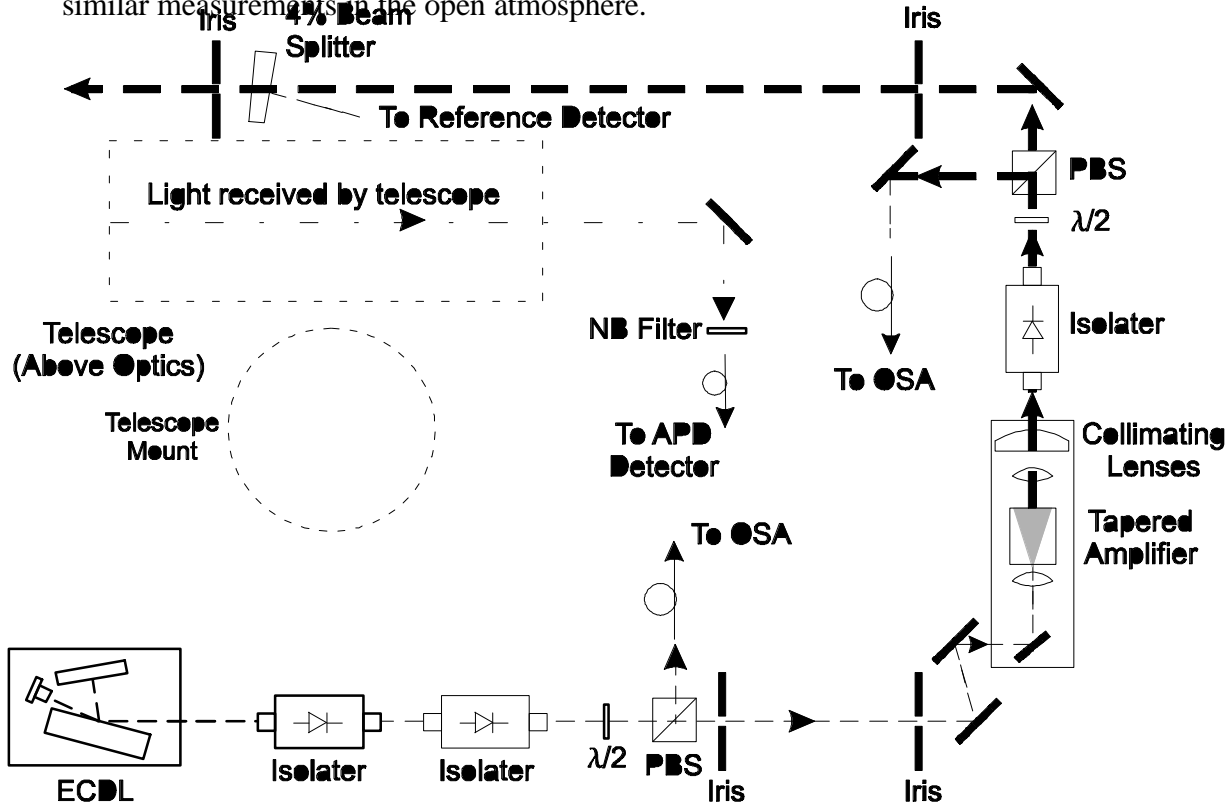


Figure 8. Schematic layout of the prototype water vapor differential absorption lidar (DIAL) system built with a tunable laser source.

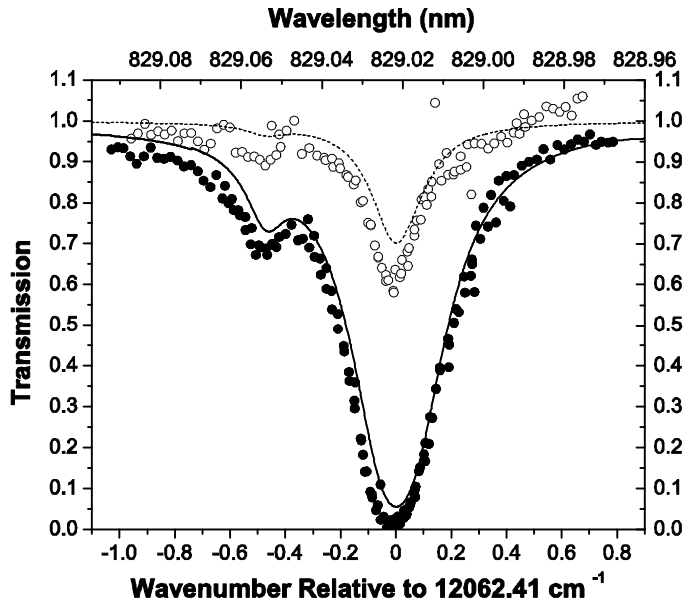


Figure 9. DIAL measurements of atmospheric transmission made as a cw laser is tuned across a water vapor absorption line at 829.022 nm with a horizontal atmospheric path. Dots are measured data and the solid lines indicate theory. The top set is for a short path length ( $\sim 0.35$  km) and the bottom set is for a longer path length ( $\sim 1.7$  km).

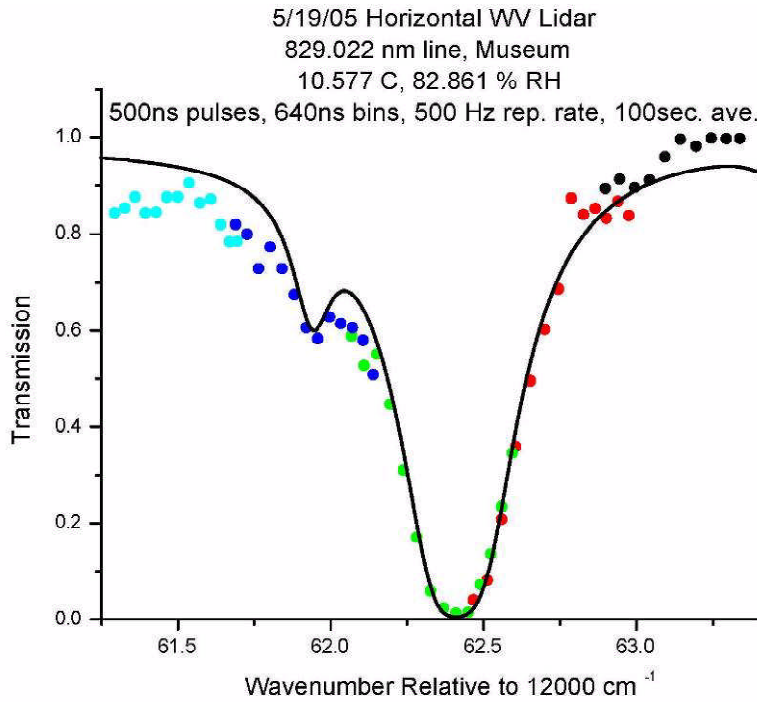


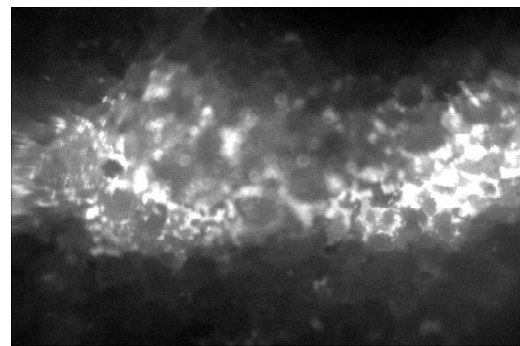
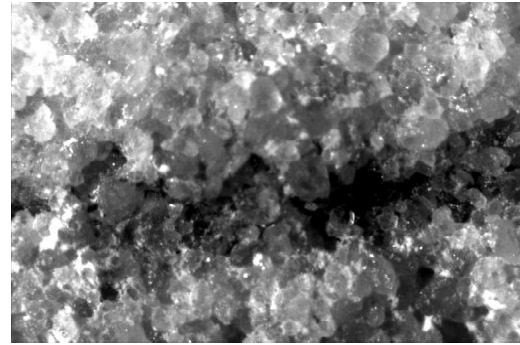
Figure 10. Pulsed DIAL measurements of relative atmospheric transmittance across a 829.022 nm water vapor absorption line, with a 1.7-km horizontal atmospheric path.

### **C. CMaRS confocal microscope and Raman spectrometer Antarctic Field Trial Opportunity**

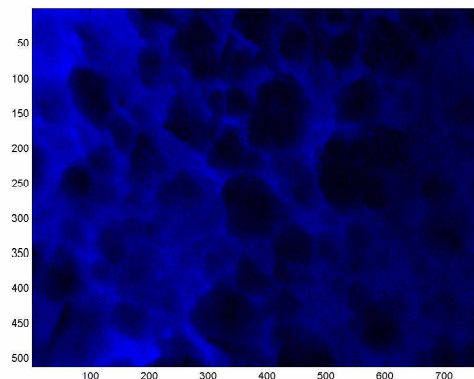
The primary activity was an opportunity for field testing of the CMaRS portable confocal microscope and Raman spectrometer (developed under a previous project) in collaboration with Dr. David Wynn-Williams of the British Antarctic Survey. This grant was to cover the equipment preparation and maintenance costs, as well as travel for Dr. Dickensheets to accompany the instrument in the field. Due to the untimely death of Dr. Wynn-Williams prior to the planned trip, the field trial opportunity was lost. However, in spite of the critical missing Antarctic field data, several subsequent publications were

#### D. Fluorescence Imaging Raman Penetrometer (FIRP)

In accordance with our proposed activities (*Activity 3* and *Activity 4*) we constructed a breadboard fluorescence imaging system to study fluorescence imaging of both soils and Antarctic rock samples. This instrument made use of low power LED illumination and successfully demonstrated fluorescence imaging with both UV and Green LED excitation, for different fluorophores. Furthermore, studies using both CCD and CMOS image sensors were carried out. A design for a compact version compatible with penetrometer deployment was developed, consistent with our brassboard system. The breadboard instrumentation was used to image standard field samples of stromatolitic and endolithic microbial communities and cyanobacterial mat samples provided by David Wynn-Williams of BAS. We also imaged a variety of fuels and solvents in a soil matrix to study the usefulness of fluorescence imaging for identifying contaminated soil. The instrumentation and study results are contained in the Master's Degree project report of Youssef Kadiri, "Soil penetrometer with Raman sampling, fluorescence and reflected light imaging: a feasibility study."



Top: CCD image of Beacon sandstone with endolithic bacterial layer (dark band). Bottom: same sample imaged using fluorescence imaging;  $\bullet_{\text{ex}}=500 \text{ nm}$ ,  $\bullet_{\text{em}}>550 \text{ nm}$ . The fluorescence imaging helps to identify the dark region as biotic material.



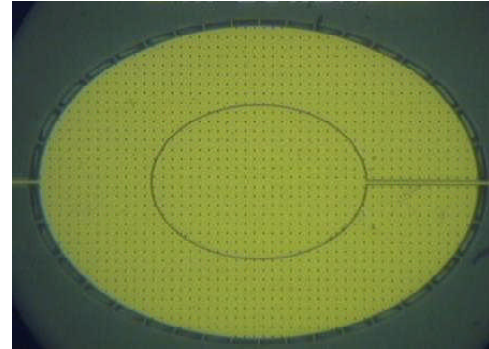
Fluorescence image of soil saturated with diesel fuel; illumination with an ultraviolet LED at 372 nm and detection at  $\bullet>420 \text{ nm}$ . Dark areas are soil grains.



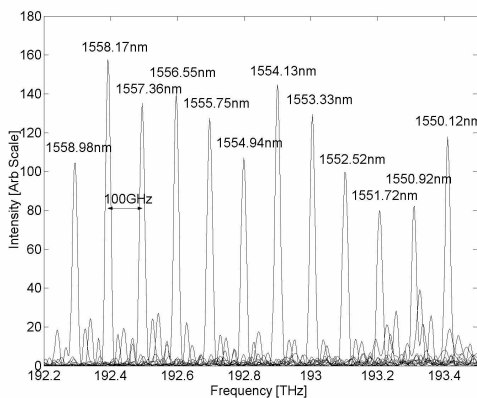
## E. MOEM Instrumentation For A Compact FT Spectrometer For Planetary Exploration

This activity provided continuing development of our unique micro-opto-electromechanical device technology for laser beam shaping and manipulation, and applied that technology to the realization of a novel optical delay element. We also demonstrated the use of that element in a Fourier Transform spectrometer.

Considerable progress was made in three areas. First, we continued to evolve our beam manipulation MOEM devices. Focus control membrane mirrors with large (5  $\mu\text{m}$ ) displacement were developed for both normal incidence and 45° incidence beams, and we characterized static and dynamic performance for fast beam focus control.

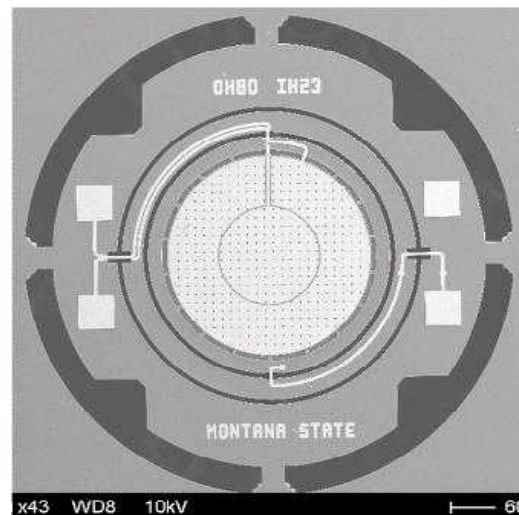


Elliptical deformable mirror for 45° incidence beam. Mirror is 1 mm x 1.41 mm, constructed from a 1  $\mu\text{m}$  thick Silicon Nitride membrane with Gold overcoating.



FTIR spectrum made using MEMS torsion-mirror addressed optical delay element.

In a parallel NSF supported project we adapted this membrane technology to create the first 3D beam control mirrors, which combine focus control with tip-tilt beam pointing. This new 3D mirror will enable future ultra-compact beam pointing and scanning instrumentation, including the type of compact FT spectrometer we studied under this grant. Second, we built a breadboard optical system to realize a



MEMS 3D mirror combining tip, tilt and focus control with a single reflecting surface.



discretely addressed optical delay element (referred to in the proposal as the Random Access Delay Line, or RADL), in which the addressing was accomplished with a MEMS pointing mirror. Feasibility was proven for this concept. Third, we demonstrated the use of the RADL element in a Fourier Transform spectrometer with 22 GHz resolution and used it to cleanly measure DWDM communications signals on a 100 GHz channel spacing in the 1.5  $\mu\text{m}$  band. The breadboard system was limited to 135 discrete delay settings in the delay line using a single-axis MEMS actuation, and had an attendant free spectral range of only 1.5 THz. But feasibility was demonstrated for an instrument that, with two-axis beam positioning, would be able to achieve 10,000 discrete delay settings with an attendant increase of the free spectral range of the system by a factor of 100. Such a system would be potentially very useful for deployment in portable FT spectrometer systems with no macroscopic moving parts in the delay element.

### III. Summary

This project led to the development of a versatile, field-deployable direct-detection lidar with a novel dual-polarization receiver, and a breadboard prototype of a water vapor differential absorption lidar using a tunable diode laser. Both systems have been used to make atmospheric measurements. The first measurement of Asian dust over Montana resulted from these measurements, in addition to a variety of instrument calibration, water vapor spectroscopy, and cloud scattering measurements. Additionally, this project led to the development of a variety of microsensor instruments and components. Future use of these sensors will contribute to advances in atmospheric science, climate science, and sensor development.

#### IV. Publications & presentations resulting from this project

##### **A. Journal papers**

1. N. L. Seldomridge, J. A. Shaw, and K. S. Repasky, "Dual-polarization cloud lidar using a  
2. liquid crystal variable retarder," *Optical Engineering* (Submitted July 20, 2005).
3. M. D. Obland, K. S. Repasky, J. A. Shaw, J. L. Carlsten, and L. S. Meng,  
"Atmospheric water vapor measured with a diode-laser differential absorption lidar,"  
*Applied Optics* (in preparation, Aug. 2005).
4. Yuhe Shao, David Dickensheets, Phillip Himmer, "3-D MOEMS Mirror for Laser  
Beam Pointing and Focus Control," *IEEE Journal Of Selected Topics In Quantum  
Electronics*, Vol. 10, No. 3, May/June 2004
5. Alex Ellery, David Wynn-Williams, John Parnell, Howell G.M. Edwards, David  
Dickensheets "The role of Raman spectroscopy as an astrobiological tool in the  
exploration of Mars" *Journal of Raman Spectroscopy* Volume: 35, Issue: 6, pp. 441 –  
457, June 2004.
6. Phillip Himmer, David L. Dickensheets, "Dynamic behavior of high-speed silicon  
nitride deformable mirrors," *SPIE* Vol. 5348, pp. 150-159, January 26-27, 2004.
7. Howell G.M. Edwards, Emma M. Newton, , David L. Dickensheets, David D. Wynn-  
Williams, "Raman spectroscopic detection of biomolecular markers from Antarctic  
materials: evaluation for putative Martian habitats," *Spectrochimica Acta Part A:  
Molecular and Biomolecular Spectroscopy* Volume: 59, Issue: 10, pp. 2277 – 2290,  
August, 2003.
8. Phillip A. Himmer and David L. Dickensheets, "Off-axis variable focus and aberration  
control mirrors," *SPIE* Vol. 4985, pp. 296-303, January 28-29, 2003.
- A. Ellery, J. Parnell, A. Steele, D. Dickensheets, H. Edwards, L. Richter, C. Kolb, H.  
Lammer, M. Patel, J. Romstedt, C. Cockell, "Astrobiological Instrumentation For  
Mars – The Only Way Is Down," *International Journal of Astrobiology*, Vol. 1 (4),  
365 – 380, 2002.
9. Howell G. M. Edwards, Emma M. Newton, David D. Winn-Williams, David  
Dickensheets, Chris Schoen, Chelle Crowder, "Laser Wavelength Selection for Raman  
Spectroscopy of Microbial Pigments in situ in Antarctic Desert Ecosystem Analogues  
of Former Habitats on Mars," *International Journal of Astrobiology*, Vol. 1 (4), 333-  
348, 2002.
10. Ellery A, Cockell C, Edwards H, Dickensheets D & Welch C (2002) "Vanguard – a

proposed European astrobiology experiment on Mars” *International Journal of Astrobiology*, Vol. 1, (3). July 2002. pp191-199.

11. Ellery A, Wynn-Williams D, Dickensheets D, Edwards H, Welch C, Curley A (2002) “Design options for a new European astrobiology-focussed Mars mission – Vanguard” World Space Congress 2002, Houston, USA, paper no. IAC-02-Q.3.2.04, October 2002.

## **B. Conference papers in printed proceedings**

1. M. D. Obland, L. S. Meng, K. S. Repasky, J. A. Shaw, J. L. Carlsten, “Progress toward a water vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source,” *SPIE Proceedings* **5887** (Lidar Remote Sensing for Environmental Monitoring VI, U. N. Singh, Ed.) San Diego, CA, 2–3 Aug., 2005.
2. N. Seldomridge, J. A. Shaw, and K. S. Repasky, “Dual-polarization cloud lidar using a liquid crystal variable retarder,” *SPIE Proceedings* **5888** (Polarization Science and Remote Sensing II, J. A. Shaw and S. Tyo, Eds.), San Diego, CA, 2–4 Aug., 2005.
3. K. S. Repasky, J. A. Shaw, J. L. Carlsten, M. D. Obland, L. S. Meng, and D. S. Hoffman, “Diode laser transmitter for water vapor DIAL measurements,” *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Anchorage, AK, 20–24 September, 2004.
4. David L. Dickensheets, Angela M. Kimmel “MOEMS Torsion Mirror Addressed Variable Optical Delay,” 2004 IEEE/LEOS International Conference on Optical MEMS, Takamatsu, Kagawa, Japan, pp 34-35, August 22-26, 2004.

## **C. Other conference presentations and seminars**

1. N. L. Seldomridge, J. A. Shaw, and K. S. Repasky, “Dual-polarization lidar measurements of Asian dust over Bozeman, Montana,” Optical Technology Center (OpTeC) annual meeting, Montana State University, Bozeman, MT, 22–23 Sept., 2005.
2. M. D. Obland, K. S. Repasky, J. A. Shaw, J. L. Carlsten, L. S. Meng, “Progress toward a diode-based differential absorption water vapor lidar,” Optical Technology Center (OpTeC) annual meeting, Montana State University, Bozeman, MT, 22–23 Sept., 2005.
3. J. A. Shaw, K. S. Repasky, J. L. Carlsten, and L. H. Spangler, M. D. Obland, N. J. Pust, N. L. Seldomridge, R. Scheppele, “Optical remote sensing research at MSU,” 2<sup>nd</sup> Annual Montana Aerospace Conference, Great Falls, MT, 23-24 Feb., 2005.
4. J. A. Shaw, “Lasers and critters: measuring bees and fish with lidar,” Physics dept.

colloquium, Montana State University, Bozeman, MT, 23 Apr., 2004.

5. J. A. Shaw, "Fishing with a laser and other short stories of electro-optical remote sensing," IEEE Montana Section meeting, Montana State University, Bozeman, MT, 24 Feb., 2004.
6. A.Ellery, A.Ball, P.Coste, D.Dickensheets, H.Hu, R.Lorenz, H.Nehmzow, G.Mckee, L.Richter and A.Winfield, "A robotic triad for Mars surface & sub-surface exploration" i-SAIRAS2003, Nara, Japan, May 24, 2003
7. M. Obland, L. Meng, K. Repasky, J. A. Shaw, and J. A. Carlsten, "Water Vapor Differential Absorption Lidar Using Tunable Diode Lasers," Optical Technology Center Annual Meeting, Montana State University, Bozeman, MT, 19–20 Sept., 2003.
8. N. Seldomridge and J. A. Shaw, "The Multiple Application Montana Lidar (MAML)," Optical Technology Center Annual Meeting, Museum of the Rockies, Montana State University, Bozeman, MT, 13–14 Sept., 2002.
9. M. Obland, J. A. Shaw, K. Repasky, L. Meng, and J. A. Carlsten, "A miniature water vapor differential absorption Lidar," Optical Technology Center Annual Meeting, Museum of the Rockies, Montana State University, Bozeman, MT, 13–14 Sept., 2002.
10. J. A. Shaw, "Overview of the Optical Remote Sensor Laboratory," Optical Technology Center Annual Meeting, Museum of the Rockies, Montana State University, Bozeman, MT, 13–14 Sept., 2002.
11. J. A. Shaw, "Optical remote sensing systems research at MSU," Montana Aerospace Conference, Fairmont Hot Springs, MT, 26 Feb., 2004.
12. K. S. Repasky, "Introduction to the lidar program at Montana State University," Optical Technology Center colloquium, Montana State University, Bozeman, MT, Dec. 2003.
13. K. S. Repasky, "Novel laser sources, science, and applications," Physics Colloquium, Montana State University, Bozeman, MT, March 2003.

#### V. Patents

*Inventor:* David L. Dickensheets

*Invention Title:* Torsion Mirror Delay Line for Potential Use in Polarization Mode Dispersion Compensation

*Disclosure/ Patent Application/ Patent #:* DD-2003-Torsion (Provisional allowed to expire)

*Inventors:* Kristian Merkel, William Randall Babbitt, Tiejun Chang, Zachary Cole, Krishna Rupavatharam, and Kelvin Wagner

*Invention Title:* The Spatial-Spectral Coherent Holographic Integrating Processor

*Disclosure/ Patent Application/ Patent #:* 10/515,089 (US only)

*Inventors:* Kristian D. Merkel, Todd Harris

*Invention Title:* Wideband Lightwave Frequency Chirp Synthesizer Apparatus for Optical Spectrum Analysis

*Disclosure/ Patent Application/ Patent #:* PCT/US04/14,019 (US and Foreign)

## VI. Students supported on the project

### A. Graduate students

Michael Obland	2003-present	(Ph.D. physics)
Nathan Seldomridge	2003-2005	MS Electrical Engineering
Nathan Wilson	2004-present	(Ph.D. physics)
Youssef Kadiri	2004	MS Electrical Engineering
Phillip Himmer		Ph.D. Electrical Engineering

### B. Undergraduate students

David Hoffman  
Amin Nehrir  
Paul Nugent  
Nick Jurich  
Dustin Dunkle